Vertical Hydraulic Conductivity Measurements in the Denver Basin, Colorado[1]

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ABSTRACT

The Denver Basin is a structural basin on the eastern flank of the Rocky Mountain Front Range, Colorado, containing approximately 3000 ft of sediments that hold a critical groundwater resource supplying many thousands of households with water. Managing this groundwater resource requires understanding how water gets into and moves through water-bearing layers in a complex multiple-layered sedimentary sequence. The Denver Basin aquifer system consists of permeable sandstone interbedded with impermeable shale that has been subdivided into four principle aquifers named, in ascending order, the Laramie-Fox Hills, Arapahoe, Denver, and Dawson aquifers. Although shale can dominate the stratigraphic interval containing the aquifers, there is very little empirical data regarding the hydrogeologic properties of the shale layers that control groundwater flow in the basin. The amount of water that flows vertically within the basin is limited by the vertical hydraulic conductivity through the confining shale layers. Low vertical flow volumes translate to low natural recharge rates and can have a profound negative impact on long-term well yields and the economic viability of utilizing the resource.

To date, direct measurements of vertical hydraulic conductivity from cores of fine-grained sediments have been published from only five locations; and the data span a wide range from $1x10^{-3}$ to $1x10^{-11}$ cm/sec. This range may be attributable, in part, to differences in sample handling and analytical methods; however, it may also reflect subtle differences in the lithologic characteristics of the fine-grained sediments such as grain-size, clay mineralogy, and compaction that relate to position in the basin. These limited data certainly call for the collection of additional data.

INTRODUCTION

The Denver Basin is a structural basin on the eastern flank of the Rocky Mountain Front Range. In eastern Colorado, approximately 3000 ft of section within this structural basin holds a critical groundwater resource that supplies hundreds of thousands of households with water. Extending south from Greeley to Colorado Springs and east from Golden to Limon, the Denver groundwater basin covers an area of nearly 6700 mi^2 (Fig. 1). Encompassing much of the Denver metropolitan region, the water resource within these basin-fill sediments is being increasingly exploited, particularly

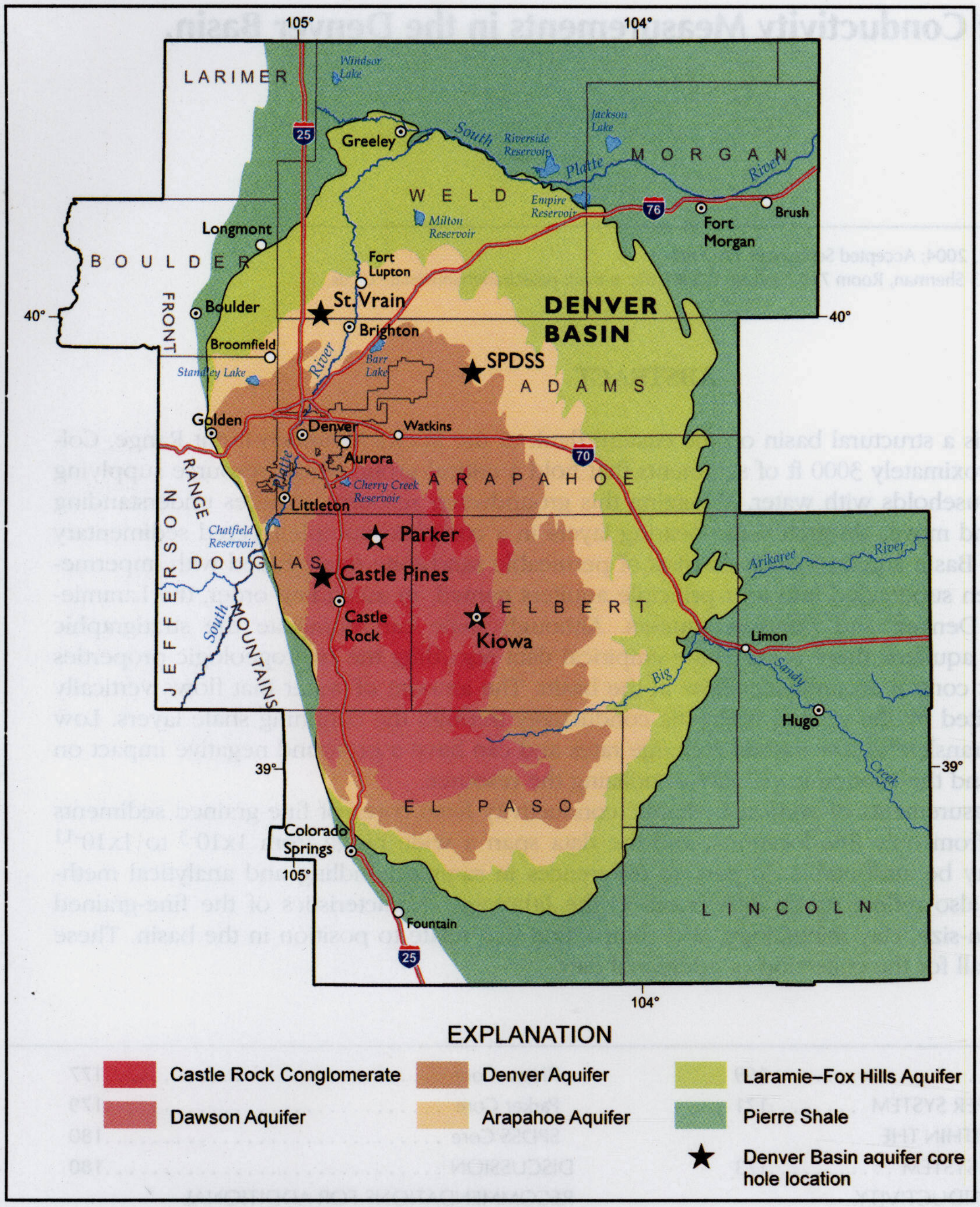

Figure 1. The Denver Basin aquifer system covers an area of nearly 6700 mi^2, based on the distribution of the Laramie-Fox Hills aquifer; but vertical hydraulic conductivity data from core samples have been published from only five locations in the Basin. Modified from Topper et al., 2003.

southeast of Denver in rapidly growing area Arapahoe and Douglas counties where surface water supplies are scarce.

Managing this groundwater resource requires understanding how water gets into and moves through water-bearing layers in a complex sedimentary sequence. This understanding must be built upon a sound knowledge of the geometry of the many sedimentary facies comprising the sequence and the hydrogeologic properties of each of the sedimentary rock types preserved in the sequence that control groundwater flow. The Denver Basin aquifer system consists of permeable sandstone interbedded with impermeable shale. With data from over 4200 geophysical logs, the geometry of the sedimentary sequence can be fairly well interpreted. Indeed, a comprehensive picture of the complex architecture of the sedimentary package is emerging, as described elsewhere in this issue. Public agencies and many private and semi-private water providers have gathered a wealth of data pertaining to the hydrogeologic properties of the aquifers. However, much of the hydrogeologic data gathered to date pertains to the aquifers on the whole and less to the individual layers that comprise them.

A comprehensive understanding of groundwater flow in the Denver Basin will require hydrogeologic characterization of individual layers within the aquifers. Deciphering the characteristics should not be limited to the water-bearing layers, but should also be extended to the less-permeable shale intervals, which restrict groundwater flow throughout the entire system. The interbedded nature of the sedimentary package and geometric shape of the water-bearing intervals imply that the hydraulic characteristics of the shale intervals are critical to the behavior of the entire sequence. Ultimately, long-term yields from wells tapping the resource will depend to a certain extent on how quickly water moves vertically from one water-bearing sand interval to another. Yet, empirical data from samples of the shale layers are available from only five locations across the Basin.

THE DENVER BASIN AQUIFER SYSTEM

Consisting of a thick sequence of Paleogene and Upper Cretaceous (about 49 to 69 Ma [Raynolds, 2002]) interbedded sandstone, conglomerate, and shale, the Denver Basin aquifer system has been subdivided into four principal aquifers named in ascending order, the Laramie-Fox Hills, Arapahoe, Denver, and Dawson aquifers (Fig. 2A). This nomenclature has been fixed by statute for the purposes of allocating water within the Basin, and many legal decrees granting water rights using this nomenclature have been granted to date.

Shale, herein used to include shale, claystone, mudstone, and muddy siltstone as variously described in the literature, is present throughout the entire sequence. Specific shale intervals identified in geophysical logs and correlated between boreholes have been used to separate the principal aquifers (VanSlyke, 2001).

The Laramie-Fox Hills aquifer is at the base of the aquifer system and consists of the 150- to 200-ft thick fine-grained Fox Hills Sandstone, and a 50- to 100-ft thick fine- to medium-grained sandstone in the overlying Laramie Formation (Robson, 1987). A thin (5-20 ft) shale separates the Fox Hills Sandstone from sandstones in the Laramie Formation. The upper 400 to 500 ft of the Laramie Formation consists of shale with coal seams and minor amounts of siltstone and sandstone. The sedimentary rocks forming the Fox Hills Sandstone and Laramie Formation were deposited by the regression of the Cretaceous Western Interior Seaway prior to, or at the inception of, subsidence of the Denver Basin (Raynolds, 2002). The Laramie Formation forms a confining layer between the Laramie-Fox Hills aquifer and the overlying Arapahoe aquifer.

Next is the Arapahoe aquifer, which is perhaps the most important aquifer in use due to its greater saturated thickness over an extended area combined with generally higher hydraulic conductivity values, and, hence, higher overall transmissivity. This aquifer consists of a 400- to 700-ft thick sequence of Upper Cretaceous interbedded conglomerate, sandstone, siltstone, and shale (Robson, 1987). Individual sandstone bodies within the Arapahoe aquifer are believed to be lens-shaped and range in thickness from less than a foot to 40 ft or more. The sandstone lenses can be closely spaced and hydraulically connected, forming a relatively uniform hydraulic unit. The net thickness of the water-bearing sandstone and conglomerate generally ranges from 200-300 ft, although the net sand thickness can exceed 400 ft. These sedimentary rocks were deposited in a synorogenic fluvial environment wherein sediments were being shed from the emerging Laramide Front Range uplift to the west and deposited by rivers and streams in the subsiding Denver structural basin (Raynolds, 2002). A layer of shale up to 50 ft thick generally separates the Arapahoe aquifer from the overlying Denver aquifer (VanSlyke, 2001).

The Denver aquifer occurs in Upper Cretaceous and Paleogene interbedded shale, claystone, siltstone, lignitic coal, and sandstone (Robson, 1987) with a total thickness approaching 1000 ft. As with the Arapahoe aquifer, these rocks were deposited in a synorogenic fluvial environment as the Laramide Front Range continued to rise and the Denver structural basin subsided. Individual sandstone bodies are also lens-shaped, however, shale is more prevalent and the sandstone bodies are less likely to be interconnected. The total thickness of the saturated sandstone within this interval generally ranges from 100 to 350 ft. A shale layer averaging 25 to 50 ft thick generally separates the Denver aquifer from the overlying Dawson aquifer (VanSlyke, 2001).

At the top of the Denver Basin aquifer system is the Dawson aquifer, consisting of Paleogene conglomeratic to coarse-grained arkosic sandstone interbedded with claystone and shale (Robson, 1987). These sediments were deposited in fluvial environments in the subsiding Denver Basin with sand coming from the rising Front Range to the west. They reach a total thickness of over 1000 ft in the center of the Basin. The water-bearing sandstone and conglomerate of the Dawson is up to 400 ft thick.

The subdivision of the sedimentary sequence holding the Denver Basin aquifer system is simplistic in its layer-cake concept, but it allows an orderly allocation of the water resource. However, it belies the complexity of the geology, much of which has come to light with the growing body of subsurface data made available as the resource is being developed. Since the synorogenic basin was being filled with clastic sediments derived from the rising Front Range to the west, there is considerable horizontal variability

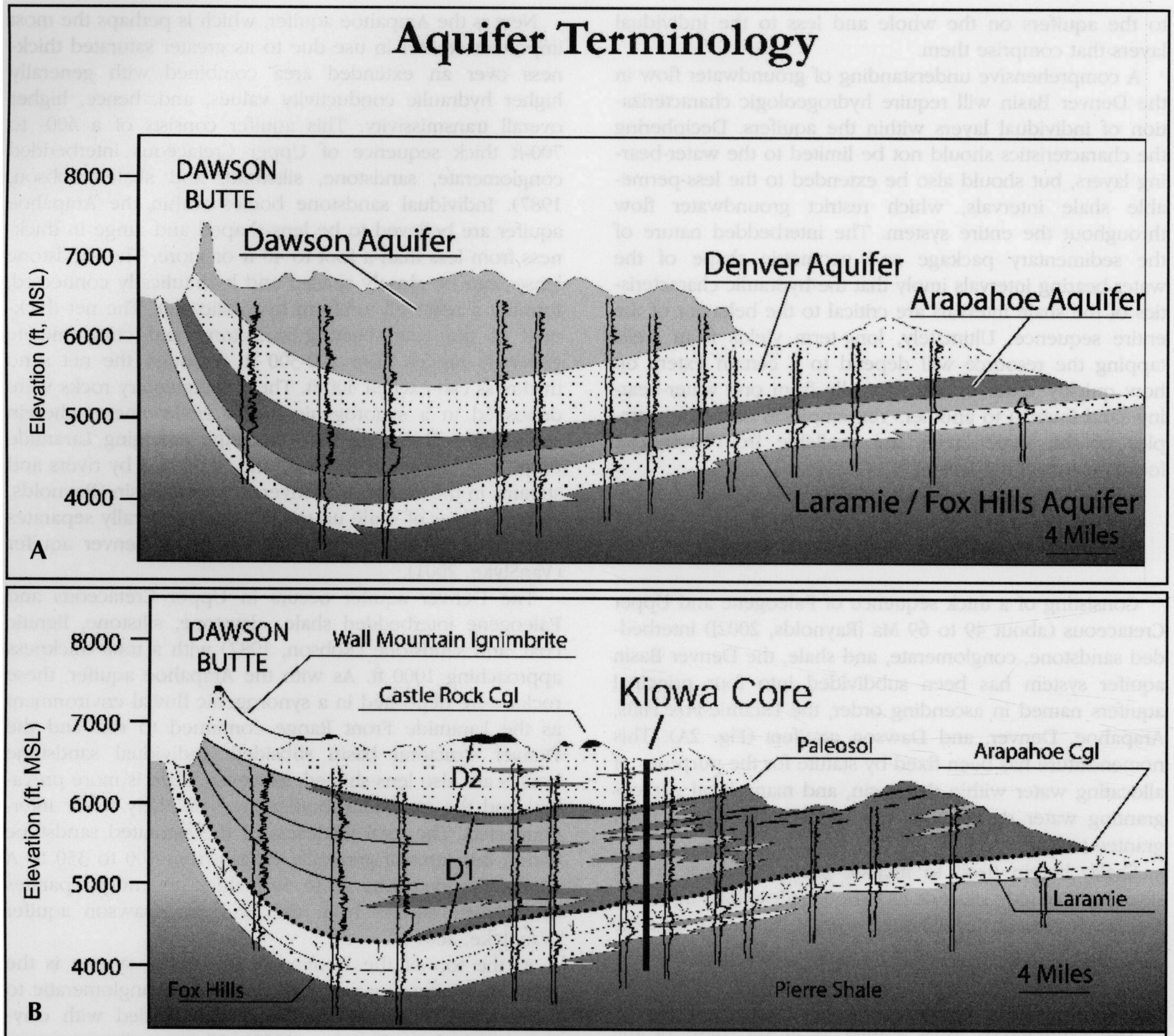

Figure 2. A. The principal aquifers of the Denver Basin aquifer system consist of interbedded sandstone, conglomerate and shale that have been subdivided into four principal aquifers separated by specific shale beds identified in geophysical logs. **B.** Recent stratigraphic interpretations of the Denver Basin subdivide the synorogenic sediments into two primary units, D1 and D2. Detailed analysis of geophysical logs from hundreds of water wells further reveals great lateral variability in the sediments with coarser grains near the sediment source to the west grading to finer-grained shaly sediments across the basin to the east. From Raynolds, 2002.

in the characteristics of the sediments filling the basin. Generally, the coarser-grained sediments found closer to the source on the west give way eastward across the Basin to finer-grained, shale-dominated sediments (Raynolds, 2002). Figure 2B illustrates this horizontal variability. This relationship is also apparent in net saturated sand and transmissivity maps of the Basin (Topper et al., 2003). Furthermore, detailed paleontological work combined with mapping of well-developed soil horizons (paleosols) within the sedimentary package in the years following the statutory definition of the Denver Basin aquifers has led to a new interpretation delineating the synorogenic sequence into two primary sedimentary packages identified as the D1 and D2 sequences (Raynolds, 2002).

Two critical characteristics influencing the hydrologic behavior of the aquifer system are the relative proportion of fine-grained sediments and the overall geometry of fluvial channel-deposited, coarse-grained, water-bearing intervals interlaced with fine-grained over-bank sediments. Fine-grained sediments tend to dominate the sedimentary sequence; particularly within the Denver aquifer, where the net saturated sand thickness is at most 35% of the total thickness of the unit interval (Robson, 1987). As pointed out above, this shale-dominance increases to the east, away from the sediment source area.

Not only do fine-grained sediments tend to dominate the Basin, but also the lenticular fluvial channel sand bodies are interpreted to be separated by shale, and therefore are believed to be poorly interconnected hydraulically (Nielsen, 2001). Figure 3 shows geophysical logs from a pair of production wells in northern Douglas County that include nearly all of the Denver aquifer and the entire Arapahoe aquifer. Shale clearly dominates the interval covered by these two logs. Furthermore, many of the water-bearing sandstone layers vary considerably in thickness even though these wells are within 100 ft of each other. The limited lateral extent of the water-bearing sandstone layers trapped within relatively impermeable shale that is most evident in the Denver aquifer portion of the logs; this geometry suggests limited hydraulic interconnection throughout this interval.

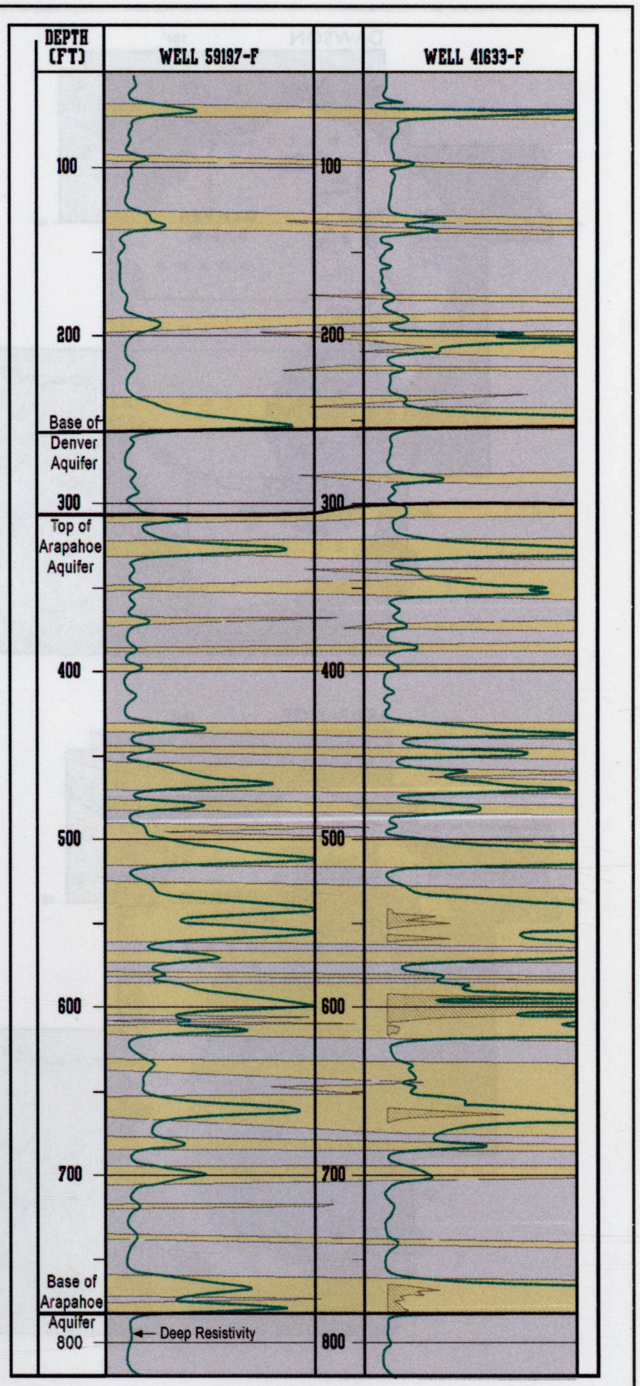

Figure 3. Resistivity logs from two production water wells less than 100 ft apart in T6S, R68W in Douglas County show the great lateral variability in thickness of many of the individual water-bearing sandstone layers. The dominance of shale within the sequence is clearly evident in the Denver aquifer. Provided by Glenn Graham, Colorado Division of Water Resources.

GROUNDWATER FLOW IN THE DENVER BASIN AQUIFER SYSTEM

Groundwater flow in the Denver Basin aquifer system is complex, given the vastness of the aquifers and the complexity of the sedimentary package. The USGS has developed a concept of the flow system (Robson, 1987) that, by necessity, is relatively simple in order to form a foundation for describing the dynamics of the resource and to predict how the resource will respond to development. The conceptual model also conforms to the layered aquifer system fixed by statute. In this conceptual model, groundwater recharges an individual aquifer by infiltration of precipitation and/or vertical flow from another aquifer. Groundwater discharges from the aquifer by: 1) outflow to connected surface water; 2) flow to an underlying aquifer; or 3) by pumping.

Unfortunately, there are few empirical data that can be used to describe groundwater flow conditions in the aquifer system prior to development; however, the USGS has used 1978 as a time starting point when development was relatively minor given the vastness of the resource. Groundwater flow in the four principal aquifers using the 1978 benchmark was believed to have been generally outward from the southern part of the Basin in the vicinity of the Palmer divide topographic high (Fig. 4). The majority of flow was directed north toward the South Platte River (Robson, 1987). A water budget for the principal aquifers

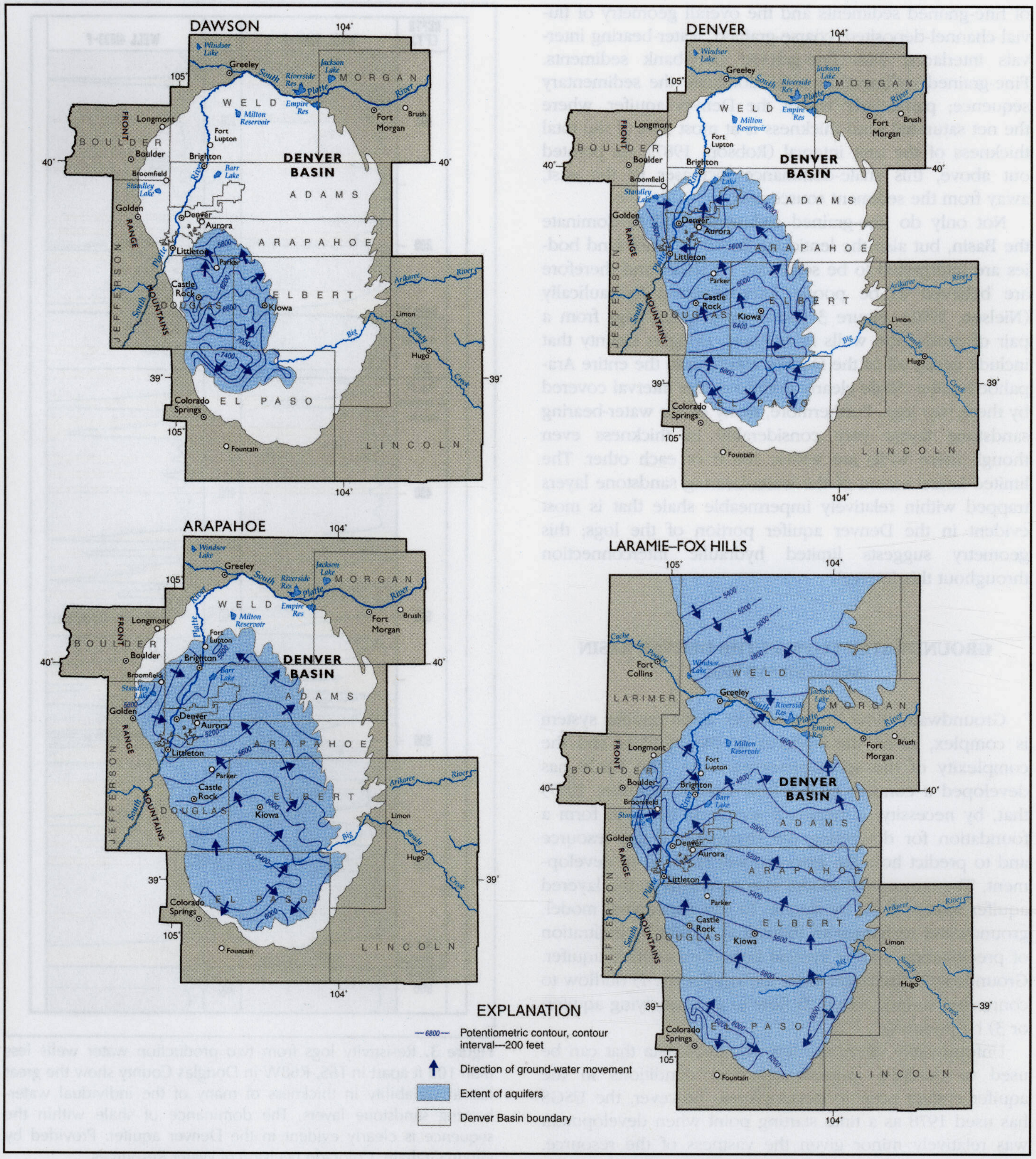

Figure 4. Horizontal groundwater flow in each of the Denver Basin aquifers in 1978 estimated by the USGS before large-scale development of groundwater in the southeastern area of the Denver metropolitan area. From Topper et al., 2003.

estimated by the USGS using computer modeling is summarized in Table 1 and includes estimates for both horizontal discharge through the four aquifers as well as interflow between the aquifers. For this paper, the important values are the vertical flow estimates, which are significant volumes ranging between 1350 and 5200 acre-ft/yr.

The USGS also used estimates for vertical hydraulic conductivity in the modeling efforts that resulted in the estimated water budget shown in Table 1 (Robson, 1987). These estimates of vertical hydraulic conductivity, listed in Table 2, were arrived at through calibration of the model wherein aquifer parameters were adjusted until model results closely matched known conditions of the aquifer and are reasonable values for the type of geologic materials. Subsequent modeling efforts, such as those used for the Senate Bill 74 (SB-74) investigations (CWCB, 1996) and the South Metro Study (Black and Veatch, et al., 2004), which stems off of the SB-74 efforts, have arrived at equivalent values for vertical hydraulic conductivity through similar groundwater modeling.

The USGS model also assumed that there was vertical connection within the aquifers and that the aquifers would remain confined for an extended period of time. Recent rapid water level decline rates in excess of 30 ft/yr that continue to decline at this rate on the west side of the basin where the aquifers rise near the Front Range, even after the water levels drop below the tops of the aquifers, would suggest that the vertical connection within the aquifers is less than originally assumed.

This conceptual model treats the Denver Basin aquifers as a relatively simple seven-layer system based on each designated aquifer along with the separating confining layers. In reality, the real-world aquifer system consists of many more individual layers of varying geometry and with varying degrees of interconnection as previously described. It is likely that each individual water-bearing sandstone or conglomerate layer, in effect, can be treated as an individual aquifer.

Not only is a scientifically based understanding of vertically hydraulic conductivity within the sedimentary sequence

Table 1.
Model derived water budget for the four main Denver Basin aquifers. Positive numbers indicate flow into the aquifer and negative numbers indicate flow out of the aquifer. Based on a transient-state 20-yr groundwater model. Adapted from Robson, 1987.

	Precipitation Recharge (acre-feet per year)	Groundwater Discharge (acre-feet per year)	Net Inter-aquifer flow (acre-feet per year)
Dawson	29,400	-24,200	-5,200
Denver	4,000	-5,350	1,350
Arapahoe	2,050	-5,900	3,850
Laramie-Fox Hills	4,200	-4,200	0
Total	39,650	-39,650	0

Table 2.
Model-derived vertical hydraulic conductivity values. A from Robson (1987); B from Barkmann and Edington, 2001).

Source	Method	Layer	Vertical Hydraulic Conductivity (cm/sec)
Robson, 1987	Model Derived	Laramie confining layer	0
		Arapahoe-Denver confining layer	9.17×10^{-9}
		Denver-Dawson confining layer	1.23×10^{-8}
Edington	Model Derived	Denver Basin confining layers	1.76×10^{-7}

critical to characterizing basic groundwater flow of the entire aquifer system, but it is also critical to understanding well performance in multi-layered aquifers. There is uncertainty about how the presence of layering within each aquifer will affect pumping capacities in individual wells as regional water levels drop below the top of the designated aquifers. It is believed that pumping capacity will be reduced more significantly than theory would predict (Black and Veatch, et al., 2004). This has profound economic ramifications on the overall performance of water supply wells, since rapidly diminishing well yields will necessitate installing more wells and expanding the supporting infrastructure in order to produce an equivalent volume of water; hence, a much higher unit cost for water.

Recent simulations performed as part of the South Metro Water Supply Study (Black and Veatch, et al., 2004) included a sensitivity analysis wherein different vertical hydraulic conductivity values of the shale layers in a multi-layered aquifer were used in mathematical simulations used to predict how well performance may decline over time as regional water levels decline (Palumbo, 2004). Changes of one or two orders of magnitude in vertical hydraulic conductivity resulted in very significant differences in predicted well performance as shown in Figure 5. This relationship underscores the need for understanding and quantifying vertical hydraulic conductivity throughout the aquifer system.

VERTICAL HYDRAULIC CONDUCTIVITY MEASUREMENTS

The hydrologic properties of each of the aquifers have been fairly well documented (Robson, 1983, 1987). However, the characterization of aquifer parameters focuses on the ability of an aquifer to yield water to wells, or to transport water through the aquifer. Direct measurements on the scale of an aquifer typically involve pumping tests wherein analytical methods allow interpretation of drawdown data to arrive at estimates of transmissivity, hydraulic conductivity, and storage capacity (Moore, 2002). It is also possible to estimate leakage values for overlying confining units (Lohman, 1972). However, the parameters arrived at this way typically are average values for an entire aquifer, or at least that part of the aquifer that is open to the well in which the test is completed. By nature of the way the wells are completed in the multi-layered aquifers of the Denver Basin, with many different water-bearing sandstone layers open to the well, it is not possible to characterize individual layers.

Characterizing individual layers requires more robust testing methods such as obtaining core samples, performing straddle-packer tests over isolated layers (Robson and Banta, 1993), or other technologies including spinner flow surveys performed in conjunction with pumping tests and integrated borehole logging methods (Paillet and Pedler, 1996). While these methods may provide estimates of hydraulic conductivity for individual water-bearing layers, they still will not provide direct information about the surrounding shale intervals. Furthermore, the results would provide estimates of horizontal hydraulic conductivity, not vertical.

Direct *in-situ* measurements would provide the best representative data. However, performing *in-situ* vertical permeability measurements on individual shale layers in a basin where depths can reach 3000 ft and hydrostatic heads above

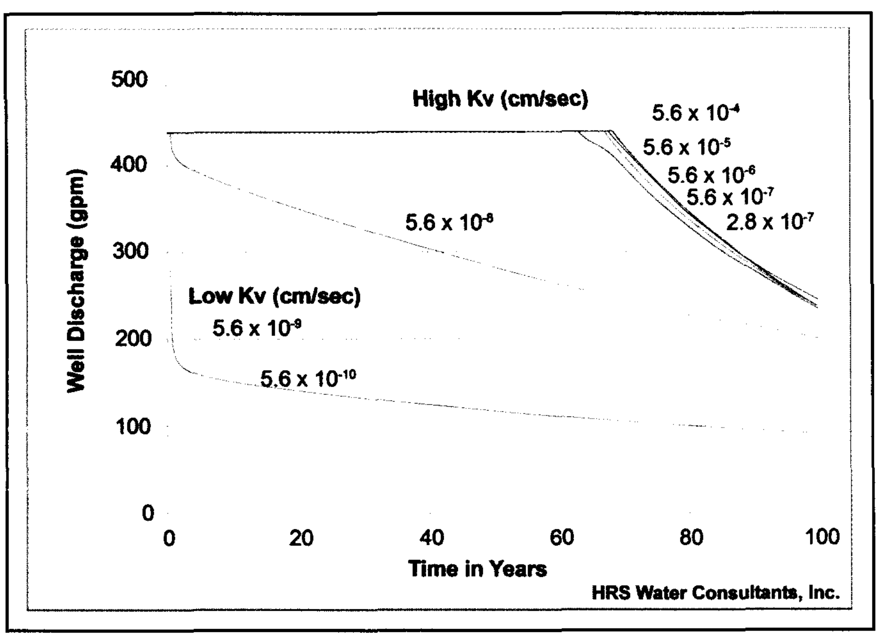

Figure 5. Mathematical model simulations used to predict well performance in an individual well as water levels in a multi-layered aquifer decline using different values for vertical hydraulic conductivity (Kv) show that very low Kv values result in rapidly declining well yields because water cannot move downward through the entire aquifer. From Palumbo, 2004.

those shale layers can exceed 2000 ft can be impractical. Measurements can also be made by installing piezometers in individual permeable layers and measuring head differences across the separating confining layers while stressing one of the layers; however, this can be costly.

From a practical perspective, vertical hydraulic conductivity of the confining shale layers is currently best measured by performing hydraulic tests on samples of the shale layers. It is also important to collect the data where the resource is being the most intensely exploited, i.e., the center of the Basin. Samples from outcrops very likely will not be representative of conditions within the basin due to weathering effects and the absence of overburden pressures. Therefore, core samples provide the best representative data; however core samples from within the Denver Basin are rare.

To date, direct measurements from cores have been published for only five locations (Fig. 1), three of which are located in close proximity to each other near the deepest part of the Basin. The other two are at the north end of the Basin near the South Platte River. The core hole projects and the hydraulic conductivity data collected from fine-grained sediments encountered in the core holes are summarized below.

Saint Vrain Core

In the late 1970s the USGS, in cooperation with the Colorado Department of Natural Resources, drilled a core hole near Saint Vrain, Weld County (Fig. 1) to evaluate the physical characteristics of the Laramie-Fox Hills aquifer (Major et al., 1983). The core hole penetrated only the Laramie-Fox Hills aquifer as the synorogenic sediments comprising the upper Denver Basin aquifers are absent in this area.

Core samples were obtained to a depth of 890.5 ft for geologic description, along with petrographic, hydraulic conductivity, and porosity analyses. Sixteen core samples were analyzed for both horizontal and vertical hydraulic conductivity using air and water (Major et al., 1983); and five of these were from shale intervals. Core Laboratories, Inc. performed intrinsic permeability analyses on plug samples taken from the cores and the results were converted to hydraulic conductivity as listed in Table 3. The results of analysis for vertical hydraulic conductivity through the shale samples collected from the Laramie-Fox Hills aquifer at this northern location in the Denver Basin range between 8.0×10^{-4} and 9.4×10^{-8} cm/sec with a median value of 7.7×10^{-5} cm/sec.

Castle Pines Core

In 1987 Castle Pines Metropolitan District and Castle Pines North Metropolitan District, through their water resources consultant Jehn and Wood, Inc., and in cooperation with the USGS, drilled two core holes near the town of Sedalia, Douglas County (Robson and Banta, 1993). Located just 7.5 miles from the western edge of the Denver Basin (Fig. 1), these core holes are relatively proximal to the source area of the synorogenic Denver Basin sediments.

Core hole C1 penetrated approximately 1,895 ft through the Dawson and Denver aquifers and into the Arapahoe aquifer where a core barrel was lost, forcing abandonment of the hole. A second core hole, C1A, approximately 28 ft away from C1, continued coring through the Laramie-Fox Hills to a depth of 3110 ft. Data collected from the core included lithologic descriptions of about 2400 ft of core and laboratory analysis of mineralogy, grain size, bulk and grain density, porosity, specific yield, and specific retention for selected core samples (Robson and Banta, 1993). From the recovered core, 33 individual samples were selected for permeability analysis. Many of the samples analyzed for permeability were collected of coarser grained-sediments in the aquifers, however, a number were reportedly collected from finer-grained intervals described as consisting of mudstone.

Permeability of the samples was measured using gas as the saturating medium. A specific method is not referenced in Robson and Banta (1993); however the source of the data is a written communication from Anthony Garcia at the Porous Media Laboratory at Colorado State University. Table 3 lists the results as hydraulic conductivity in cm/sec from 15 of the finer-grained or more poorly sorted lithologies. The results of analysis for vertical hydraulic conductivity through the finer-grain and poorly sorted lithologies collected from the Denver Basin aquifers at this western location in the Denver Basin range between 7.3×10^{-4} and 5.1×10^{-6} cm/sec with a median value of 8.6×10^{-5} cm/sec.

Kiowa Core

In 1999 the Kiowa core was obtained from a site within the town of Kiowa, Elbert County (Fig. 1), as a component of the Denver Basin Project, which is a cooperative and multidisciplinary research effort by the Denver Museum of Nature & Science to study the evolution of the Denver Basin (Raynolds et al., 2001). The site, approximately 26 miles from the western edge of the Denver Basin, was selected to be farther away than the Castle Pines core location.

The core hole penetrated 2256 ft through the Dawson, Denver, Arapahoe, and Laramie-Fox Hills aquifers and was terminated in the Pierre Shale. Approximately 93% of the rock penetrated was recovered. Core samples were handled and stored to minimize dehydration and physical disturbance (Lapey, 2001). Fifty-five samples were collected from the core for laboratory measurement of hydraulic conductivity (Raynolds et al., 2001; Lapey, 2001) and

Table 3.
Vertical hydraulic conductivity measurements from core samples of very fine-grained lithologies taken from the Denver Basin aquifers. *1) Reported as intrinsic permeability, converted to hydraulic conductivity assuming water at 56° C. 2) Reported as intrinsic permeability, converted to hydraulic conductivity assuming water at 16° C. 3) Reported as hydraulic conductivity.*

Borehole (Source)	Depth (feet)	Aquifer	Lithology	Saturating Media	Hydraulic Conductivity
Saint Vrain	357	L-Fox Hills	Shale	air	8.02E-04 1)
(Major et al., 1983)	375	L-Fox Hills	Shale	water	1.93E-06 1)
	575	L-Fox Hills	Shale	water	9.43E-08 1)
	879	L-Fox Hills	Shale	air	1.69E-04 1)
	890	L-Fox Hills	Shale	water	7.73E-05 1)
Castle Pines	377	Dawson	Graywacke	gas	1.29E-04 2)
(Robson and Banta,	392	Dawson	Graywacke	gas	8.58E-05 2)
1993)	679	Dawson	Graywacke	gas	7.29E-04 2)
	763	Dawson	Graywacke	gas	7.98E-05 2)
	797	Dawson	Silty mudstone	gas	3.78E-04 2)
	823	Dawson	Silty mudstone	gas	3.69E-04 2)
	967	Denver	Silty mudstone	gas	4.38E-05 2)
	1351	Denver	Graywacke	gas	1.03E-05 2)
	1448	Denver	Graywacke	gas	8.58E-05 2)
	1501	Denver	Graywacke	gas	1.29E-04 2)
	1537	Denver	Graywacke	gas	8.58E-05 2)
	1674	Denver	Graywacke	gas	6.09E-04 2)
	1801	Denver	Graywacke	gas	2.91E-05 2)
	1884	Arapahoe	Graywacke	gas	5.06E-06 2)
	1943	Arapahoe	Graywacke	gas	2.57E-04 2)
Kiowa	91.5	Dawson	Muddy sandstone	water	7.52E-05 3)
(Lapey, 2001)	100	Dawson	Silty mudstone	water	1.35E-04 3)
	180.5	Dawson	Silty mudstone	air	2.71E-04 3)
	286.1	Dawson	Muddy sandstone	water	5.78E-07 3)
	339.1	Dawson	Sandy mudstone	water	8.53E-08 3)
	387.2	Denver	Sandy mudstone	water	9.80E-05 3)
	428.5	Denver	Silty mudstone	water	3.90E-07 3)
	480	Denver	Silty mudstone	water	3.81E-05 3)
	600	Denver	Mudstone	water	1.71E-06 3)
	851.7	Arapahoe	Sandstone	air	3.73E-06 3)
	1245.6	Arapahoe	Silty mudstone	water	1.61E-06 3)
	1297.7	Arapahoe	Siltstone	water	1.46E-05 3)
	1349.5	Arapahoe	Siltstone	water	1.25E-05 3)
	1528	Arapahoe	Sandstone	water	8.88E-07 3)
	1590	Arapahoe	Sandy mudstone	water	3.87E-06 3)
	1623.6	Arapahoe	Sandstone	water	1.49E-07 3)
	1634.9	Arapahoe	Muddy conglomerate	water	3.11E-07 3)
	1749	Arapahoe	Sandy mudstone	water	3.42E-05 3)
	1846.3	L-Fox Hills	Silty mudstone	water	1.65E-05 3)
	2046.4	L-Fox Hills	Sandy mudstone	water	6.68E-06 3)
	2183.9	L-Fox Hills	Limey sandstone	water	3.43E-07 3)
	2242	L-Fox Hills	Silty mudstone	water	1.98E-07 3)
Parker	1230.9	Denver	Silty shale	water	2.57E-11 2)
(Barkmann and	1245.8	Denver	Silty shale	water	1.72E-11 2)
Edington, 2001)	1373.5	Arapahoe	Shaley sand	water	3.43E-11 2)
	1378.1	Arapahoe	Sandy shale	water	1.72E-11 2)
	1585.5	Arapahoe	Silty shale	water	7.72E-11 2)
	1587	Arapahoe	Silty shale	water	3.78E-10 2)
	1599.6	Arapahoe	Silty shale	water	1.72E-10 2)
	1705.9	Arapahoe	Silty shale	water	3.43E-11 2)
	1706.6	Arapahoe	Silty shale	water	1.31E-09 2)
	1710.7	Arapahoe	Sandy shale	water	8.58E-11 2)
SPDSS	124.8	Denver	Sandy shale	water	3.53E-08 3)
(CDM, 2004)	161.1	Denver	Sandy shale	water	4.69E-06 3)

included a variety of lithologies. Laboratory analyses were conducted in accordance with American Society for Testing and Materials (ASTM) Standard D 2434-68 (ASTM, 1974). Coarse-grained samples were tested using a constant head permeameter, while the finer-grained samples were tested using a falling head permeameter (Lapey, 2001). Several of the samples were tested using an air permeameter in accordance with ASTM Standard D 4525-90 (ASTM, 1990).

Table 3 lists the results from those samples from the Kiowa core that were described as fine-grained claystone and mudstone. However, several of the coarser-grained samples had very low reported hydraulic conductivity values implying that the lithology was very poorly sorted or contained interstitial clay or cement. The results from those samples described as coarse-grain that had very low hydraulic conductivity values have been included in the table because the sedimentary layers they represent probably limit vertical hydraulic connection no differently than shale. The results of analysis for vertical hydraulic conductivity through the finer-grain and poorly sorted lithologies collected from the Denver Basin aquifers at this central location in the Denver Basin range between 2.7×10^{-4} and 8.5×10^{-8} cm/sec with a median value of 3.8×10^{-6} cm/sec. These values are lower than reported for the Castle Pines location by at least an order of magnitude, which is consistent with the greater distance from the sediment source.

Parker Core

In May 2001 the Parker Water and Sanitation District (PWSD) drilled an Arapahoe aquifer production well near the center of the town of Parker, Douglas County (Fig. 1). The location of the Rowley Downs Arapahoe well is near the deepest part of the Denver Basin, about 16 miles from the source area. As part of the drilling project, PWSD, through their water resources consultant John C. Halepaska and Associates, Inc. (JCHA), collected whole cores (Fig. 6) during the drilling of a 12-inch pilot hole to evaluate the vertical hydraulic conductivity through the confining layers separating the aquifers as well as shale layers separating individual sandstone layer within the aquifers (Barkmann and Edington, 2001).

Approximately 100 ft of 4-inch diameter whole core was recovered from six intervals in the Denver and Arapahoe aquifers at depths of 650 to 1730 ft (Barkmann and Edington, 2001). The cores targeted shale layers using geophysical logs from an existing well about 150 ft away. Following consultation with members of the Denver Basin Project team involved with the Kiowa Core project, special care was taken in handling the core to avoid physical disturbance and dehydration of the core in order to prevent altering the hydrologic properties of the recovered samples.

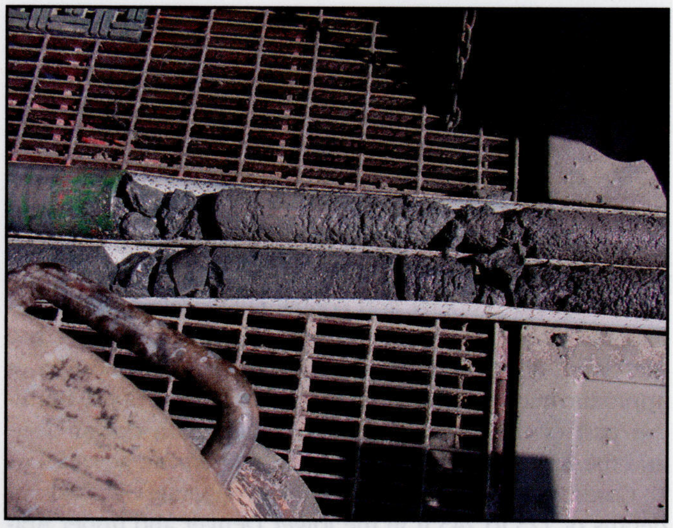

Figure 6. Shale core sample collected during the drilling of an Arapahoe aquifer well at Parker, Douglas County, CO. The samples were briefly described prior to wrapping in cellophane and being placed in sealed PVC containers to minimize dehydration and mechanical agitation. Photograph by John C. Halepaska.

From the whole cores, ten samples were analyzed for vertical hydraulic conductivity (Barkmann and Edington, 2001). Vertical plugs, 1-inch in diameter, were drilled out of each of the core samples for liquid permeability analysis by SCAL, Inc. of Midland, Texas in accordance with a modified API RP 27 and API RP 40 (1952, 1960) methods. Smaller diameter plugs were used rather than the whole core to improve the seal between the sample and permeameter ring. Midland, Texas tap water was used as the saturating medium during the analyses. As indicated in Table 3, the results of analysis for vertical hydraulic conductivity through the selected shale layers collected from the Parker well range between 1.3×10^{-9} and 1.7×10^{-11} cm/sec with a median value of 5.6×10^{-11} cm/sec.

These vertical hydraulic conductivity values reported for the Parker core samples are several orders of magnitude lower than those reported for the Kiowa core. One possible explanation is that the samples were specifically selected from the finer-grained sediments with the objective of placing a lower limit on the hydraulic conductivity of the confining layers.

The chemistry of Midland tap water may differ from that of formation water within the Arapahoe aquifer. Barkmann and Edington (2001) believe that there was little potential for changes in the clay structure that could result in lower permeability results by using Midland tap water during the testing procedure primarily due to higher salinity of the tap water and low residence time during the tests. However, the subject of clay mineralogy and reactivity to waters of varying chemistry deserves further research.

SPDSS Core

The Colorado Water Conservation Board is currently implementing its South Platte Decision Support System (SPDSS) to better manage surface and groundwater within the South Platte River Basin (CWCB, 2004). As part of the groundwater component of the SPDSS, Camp Dresser and McKee (CDM), Inc. drilled a bedrock test well in October 2003 at a site north of Bennett, Adams County (Fig. 1) to obtain aquifer property and configuration data and to evaluate the interaction between the Denver Basin aquifers and the South Platte alluvium (CDM, 2004). The location is approximately 42 miles from the western edge of the northern part of the Basin where the aquifers are not as deep and the upper Denver and Dawson aquifers are absent.

Cores were obtained from three separate intervals at depths of 125 to 245 ft in the lower Denver and upper Arapahoe aquifers. Two samples of fine-grained semi-consolidated claystone were selected from the cores for laboratory analysis of vertical hydraulic conductivity (CDM, 2004). The objective was to determine vertical leakage characteristics, with emphasis on possible hydraulic connection between the Denver Basin bedrock aquifer and the overlying South Platte alluvial aquifer. CDM (2004) took special care in handling the samples to prevent dehydration and mechanical agitation of the fine-grained sediments.

The samples were analyzed by Core Lab Petroleum Services for liquid permeability in accordance with API RP-40 methods (API, 1960) using formation water produced from the Arapahoe aquifer at the end of a pumping test (CDM, 2004). Formation water was used as the saturating medium to minimize the potential for volumetric changes in clay mineralogy and structure by the introduction of water of differing chemistry, as identified with the Parker cores. The results of analysis for vertical hydraulic conductivity from the two samples collected of fine-grained confining intervals at this location are on the order of $4.7\text{x}10^{-6}$ to $3.5\text{x}10^{-8}$ cm/sec (Table 3), which are lower than the results reported for the Kiowa core, yet higher than reported for the Parker core. Core handling and analytical methods closely followed those implemented at Parker, with the exception of the use of native formation water as the saturating media. However, the samples from the SPDSS site were also obtained from much shallower depths in the Basin, where the synorogenic sediments may have never been subjected to the same depth of burial as near the deepest part of the Basin.

DISCUSSION

The current set of empirical vertical hydraulic conductivity measurements represent a very small sampling of a vast geologic feature, not only horizontally across a nearly 6700-mi^2 basin, but also vertically through a 3000-ft thick sedimentary section. On a map basis, there are only five sets of data; and of those five sets, the maximum number of vertical data points with specific reference to finer-grained confining layers is 22. This is a very small data set, given the importance of this resource and the rate at which it is being exploited.

Even with the limited size of this data set, the range of variability among the results is large, spanning from $1\text{x}10^{-3}$ to $1\text{x}10^{-11}$ cm/sec, as shown graphically in Figure 7. Typical hydraulic conductivity values for shale fall below $1\text{x}10^{-7}$ cm/sec while values for silt range between $1\text{x}10^{-3}$ and $1\text{x}10^{-7}$ cm/sec (Freeze and Cherry, 1979). Some of this variability may be attributable to differences in the physical properties of the rocks such as lithology relative to the source area. Furthermore, not all of the values listed in Table 3 and shown in Figure 7 are from samples that are necessarily shale. There could also be differences in physical properties of the rocks owing to differences in compaction histories that may not be uniform across the Basin; not all shales are the same. On the other hand, some of the variability in analytical results probably arises from differences in methods, both from the standpoint of sample handling and analytical technique. Most of the results listed above $1\text{x}10^{-7}$ cm/sec are probably not of the shale confining layers or are not representative due to discrepancies in sample handling and testing methods.

During evaluation of the Parker core, JCHA conducted sensitivity analyses of the analytical methods on several of the samples. The first analysis consisted of performing replicate analyses using the same methods and saturating medium on the same samples in order to measure variability within the same method, while the second sensitivity analysis consisted of comparing analytical results from using water and comparing them with the analytical results from the same sample using a different method with air as the saturating medium. The results of both sensitivity analyses (Table 4) are revealing and give a sense of how critical the selection of method is and the precision of the results.

For the replicate analyses within the same method using the same saturating medium, the differences in results of analyzing the same samples are within an order of magnitude. However, the differences in the results from different methods using differing saturating media are very significant, ranging between one and five orders of magnitude. Barkmann and Edington (2001) attributed the difference between the results from the different methods to changes in the clay structure in the samples that probably occurred during preparation of the samples for analysis with air. The clays in the samples presumably remained in a maximum state of swelling as long as the samples remained hydrated; however, those same clays may have undergone shrinkage and/or cracking upon drying for the tests using air. The sensitivity analyses clearly indicate that maintaining clay structure in as near a natural state as possible is absolutely

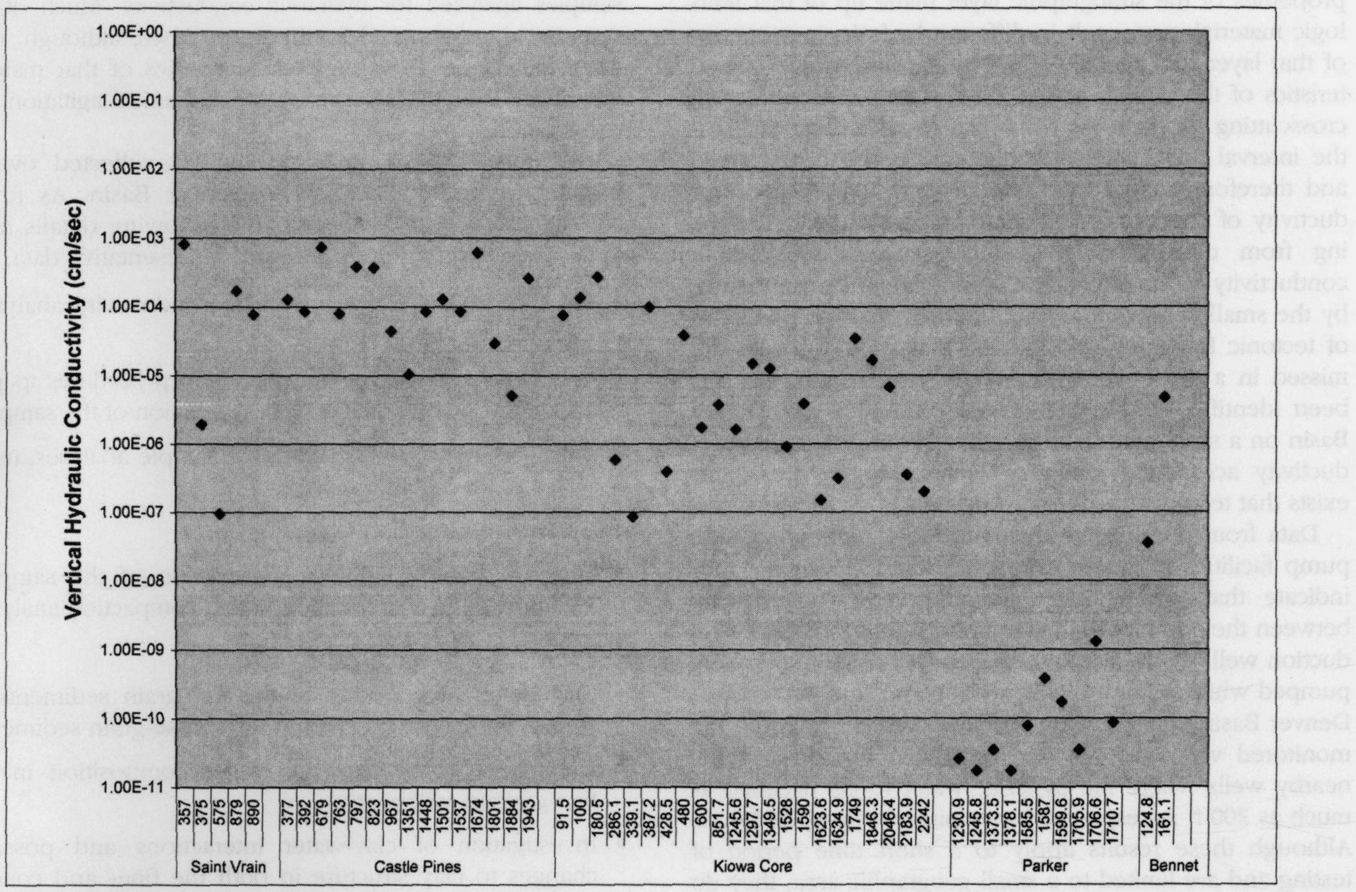

Figure 7. Results of analysis for vertical hydraulic conductivity from samples of fine-grained confining layers within the Denver Basin aquifer system span eight orders of magnitude with the lowest approaching 1×10^{-11} cm/sec. The variability may be attributable to both real differences in rock properties and differences in sample handling procedures as well as analytical technique. From Barkmann and Edington, 2001.

critical to obtaining representative hydraulic conductivity measurements of the confining layers. This also indicates that much more research needs to be done into the clay mineralogy and structure within the confining layers of the Denver Basin aquifer system.

It is also important to not lose track of the sense of scale with these analytical results. Hydraulic conductivity analyses on core samples, and in many cases, small diameter plugs taken from those cores, provide estimates of the physical properties of that material. On a larger scale, other

Table 4.

Results of sensitivity analyses performed on samples from the Parker cores show good correspondence between results within the same method using the same saturating media but great variability between using water or air as the saturating medium on the same sample. From Barkmann and Edington, 2001.

Sample depth (feet)	Hydraulic Conductivity Using Water (cm/sec)	Replicate Result Using Water (cm/sec)	Hydraulic Conductivity Using Air (cm/sec)	Replicate Result Using Air (cm/sec)
1,585.5	7.72×10^{-11}	3.43×10^{-11}	1.06×10^{-6}	
1,706.6	1.31×10^{-9}		4.03×10^{-7}	1.46×10^{-8}

properties of the stratigraphic layer made up of that lithologic material may result in different hydrologic properties of that layer that actually affect the hydrodynamic characteristics of the aquifer system. For example, there may be crosscutting stratigraphic relationships with other facies in the interval increasing hydraulic connection across layers and therefore increase the overall vertical hydraulic conductivity of the interval. Similarly, bioturbation or fracturing from diagenesis could increase vertical hydraulic conductivity of the interval on a scale larger than measured by the small core sample size. There is also the possibility of tectonic fracturing and faulting that should not be dismissed in a synorogenic basin. To date, faulting has not been identified within the central portion of the Denver Basin on a scale that could increase vertical hydraulic conductivity across the confining layers, but the possibility exists that tectonic fracturing is present.

Data from pumping tests conducted at multiple-aquifer pump facilities in Parker during May and December 2000 indicate that, locally, there is little vertical connection between the aquifers (Barkmann and Edington, 2001). Production wells completed in one Denver Basin aquifer were pumped while water levels in wells completed in the other Denver Basin aquifers were monitored. Water levels in the monitored wells did not decline during pumping of the nearby wells where the dynamic water levels declined as much as 200 ft in response to pumping for up to 48 hours. Although these results apply to a short time period of testing and are limited to a small geographic area, they do indicate limited vertical hydraulic connection between the aquifers consistent with very low hydraulic conductivity in the separating shale intervals.

With the considerable variability observed in the results of vertical hydraulic conductivity analyses on this limited set of data points, what can be said about the amount of vertical groundwater flow in the Denver Basin? These values provide a steppingstone in analyzing the system. They give end values from which to begin asking questions and with which to validate modeling efforts. Most importantly, the data suggest that the vertical hydraulic connection *between* the principal aquifers and *within* the aquifers may be very limited, changing the concept of how the aquifer system as a whole will behave as exploitation progresses.

RECOMMENDATIONS FOR ADDITIONAL DATA COLLECTION

The limited set of data reviewed here certainly begs for more research and, as always, additional raw data from a wider distribution of sites. Additional topics for research that should help resolve the uncertainty in the results published to date include, but are not limited to, robust analysis of grain-size distribution as well as degree of compaction of samples analyzed for hydraulic conductivity. Much of the core remains preserved for future analyses, although, over time, the natural hydrologic characteristics of that material have likely changed as a result of mechanical agitation and dehydration.

Additional core samples should be collected over a broader distribution across the Denver Basin. As future core sampling efforts advance, the following details need to be considered in order to obtain representative data:

- For core handling and hydraulic conductivity analytical procedures:
- Follow standardized sample handling procedures to prevent dehydration and mechanical agitation of the samples;
- Follow standardized methods for sample analyses, using water as the testing media;
- Use native formation water;
- Perform detailed lithologic description of the samples, including grain size distribution and compaction analyses.

Topics for additional investigation:

- Clay mineralogy studies of the fine-grain sediments as well as the interstitial clays in the coarse-grain sediments;
- Determination of formation water composition in the fine-grained sediments;
- Investigation of clay-water interactions and possible changes to clay structure in both the fine- and coarse-grained sediments resulting from changes in water chemistry. This will be particularly vital as artificial recharge with non-native water is implemented on a large scale across the Basin;
- Compaction studies of the fine-grained sediments relative to position in the Basin and potential maximum depth of burial.
- *In situ* testing at a number of sites across the basin using multiple piezometers completed in individual sandstone layers while pumping from deeper permeable layers.

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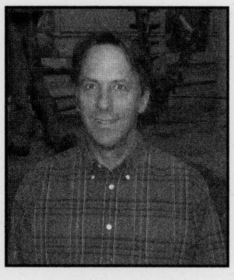

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